Chapter 5
Optimization of Biomass Transport and Logistics

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Abstract Global demand for lignocellulosic biomass is growing, driven by a desire to increase the contribution of renewable energy to the world energy mix. A barrier to the expansion of this industry is that biomass is not always geographically where it needs to be, nor does it have the characteristics required for efficient handling, storage, and conversion, due to low energy density compared to fossil fuels. Technologies exist that can create a more standardized feedstock for conversion processes and decrease handling and transport costs; however, the cost associated with those operations often results in a feedstock that is too expensive. The disconnect between quantity of feedstock

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needed to meet bioenergy production goals, the quality required by the conversion processes, and the cost bioenergy producers are able to pay creates a need for new and improved technologies that potentially remove barriers associated with biomass use.

Because of their impact on feedstock cost, feedstock location and raw physical format are key barriers to industry expansion and intercontinental trade. One approach to reducing biomass cost is to emulate the commodity fossil-fuel-based feedstocks that biomass must compete with in terms of logistics, quality, and market characteristics. This requires preprocessing the biomass to improve density, flowability, stability, consistency, and conversion performance. Making the biomass format compatible with existing high-capacity transportation and handling infrastructure will reduce the need for new infrastructure. Producing biomass with these characteristics at costs conducive to energy production requires the development of new technologies or improvements to existing ones.

5.1 The Role of Transport and Logistics in Achieving Global Bioenergy Targets

The volume of biomass required to support a bioenergy industry that is capable of realizing even just a tenth[1] of the world's bioenergy production potential is often overlooked. At full capacity, sustainable global bioenergy production potential has been estimated sufficient to offset up to 60 % of world primary energy demand (Berndes et al. 2003; Smeets et al. 2007; Campbell et al. 2008; IEA 2008), and is technically capable of providing up to 1,500 EJ/year by 2050 (Bauen et al. 2009).

To realize substantive environmental benefits of bioenergy production, such as greenhouse gas reduction of 50 % by 2050, the International Energy Agency (IEA) estimates that bioenergy production will need to provide more than 20 % of the world's primary energy, or 150 EJ/year (IEA 2008). For comparison, the U.S. Energy Information Administration (EIA) reports global bioenergy production in 2010 of 1.135 EJ/year (electricity 1.127 EJ/year and biofuels .008 EJ/year) (EIA 2013). To support increased bioenergy production to meet the 150 EJ/year production target, biomass feedstock supply systems will need to provide approximately 15 billion metric tons of biomass annually (IEA 2008; Laser et al. 2009).

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[1] Based on estimated annual world supply of 146 billion metric tons (Cuff and Young 1980).

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Currently, world biomass markets and supply chains are not well developed; however, demand is growing, particularly in densely populated areas. The wood pellet market is strong in Europe, which, in 2010, comprised about two-thirds of the total international solid biofuel trade (Lamers et al. 2012). As a result of national policies to increase renewable energy resources, markets are also emerging in China, South Korea, and Japan (Roos and Brackley 2012).

5.1.1 Geographic Incongruity of Resource Production and Energy Demand

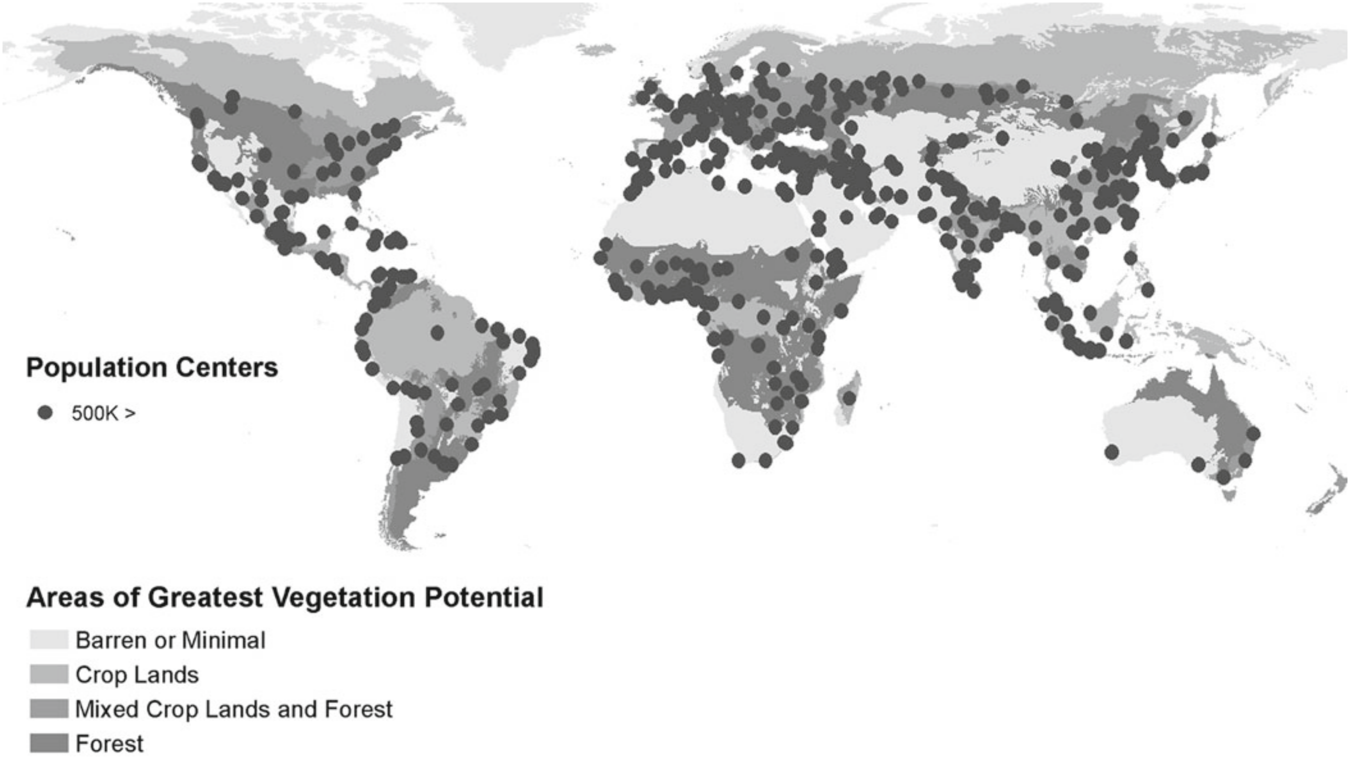
A fundamental problem for expansion of bioenergy industries is that regions rich in biomass resources are not necessarily close to the densely populated cities with the greatest energy demands, and the question that often arises is whether bioenergy resources and products can be traded outside their production areas economically and sustainably (Hamelinck et al. 2005) (Fig. 5.1).

5.1.2 Overcoming Geographic Incongruities Within Cost Constraints

As can be inferred from Fig. 5.1, achieving objectives for increased use of renewable bioenergy resources will require that biomass has the characteristics needed to be bought and sold outside of its production areas, or that biomass is “tradable.” Tradability is influenced by the reliability of product supply, the existence of a market demand, the opportunity for profitable transactions, the physical transferability of the product, and the guarantee of product quality. These influences are not exclusive of one another, and the more that must be done to a product to improve its tradability, the greater the cost constraint pressures become.

For example, in terms of physical transferability, technologies already exist to preprocess biomass into dense, flowable, storable, and easily transportable feedstocks that can be traded outside of their production areas. Unfortunately, the costs of implementing these technologies often prohibit access to these feedstocks because currently, the costs of improving their tradability keep them from being cost-competitive with the conventional energy products they are intended to replace. As a general guideline based on current states of conversion technologies, it is estimated that delivered biomass feedstock costs need to be near $80 per ton for transportation fuels and $50 to 75 per ton for heat and power. Except for minimally preprocessed feedstocks that are produced in high-yield areas and are cost-effective only for local use, addressing logistics challenges associated with tradability *within cost constraints* is a significant barrier that prevents much of the global biomass resource potential from moving into the market (Fig. 5.2).

Although reliance on local biomass resources is economically viable in a limited number of high-yield scenarios, such as the use of corn stover in the U.S. Midwest


Population Centers
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Mixed Crop Lands and Forest
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Fig. 5.1 Often the world's regions that are richest in biomass resources (*shaded areas*) are at a distance from the densely populated cities (*black dots*) where demand for energy is greatest, necessitating the transport of bioenergy resources and products outside production areas

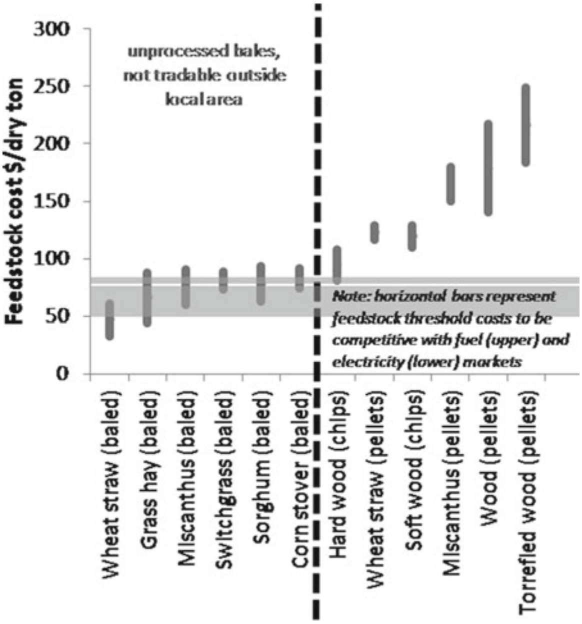

Fig. 5.2 Feedstock costs for unprocessed and preprocessed, tradable bioenergy feedstocks in comparison with feedstock threshold costs that allow biomass to be cost-competitive with fossil-fuel-based counterparts (Pami 2012; Amosson et al. 2011; Saskatchewan Forage Council 2011; Gustafson et al. 2011; Peng et al. 2010; Wood Resources International LLC. 2011; Wright et al. 2012; Nolan et al. 2010; English et al. 2013; Zhang et al. 2010; Sikkema et al. 2010)

to produce renewable transportation fuels, these scenarios do not supply sufficient biomass to support a bioenergy industry capable of achieving the 150 EJ/year production target. To expand global bioenergy production at a scale that substantively captures environmental and energy security benefits, technological advancements are needed that:

1. address the product's physical transferability challenges that currently restrict the volume of resource available
2. ensure specifications meet conversion process performance requirements, and
3. allow bioenergy products to be cost-competitive with their fossil-fuel-based counterparts.

This chapter explores these three themes in terms of feedstock “logistics”, “quality”, and “market” characteristics, with emphasis on how technological advancements can influence these characteristics by addressing transport and logistics challenges.

From a historical perspective, we consider the development of international grain and flour trading systems, with emphasis on how technology was used to improve logistics, quality, and market characteristics, and, in turn, facilitate significant industry expansion. We discuss similar implementation of technologies to improve tradability of biomass resources, and the tipping point characteristics that both meet logistics and quality requirements for tradability but currently fall short of satisfying international tradability because of economics requirements. Some of the logistics challenges specific to intercontinental transport are presented. Finally, we discuss the potential of using advanced preprocessing technologies in combination with densification and feedstock formulation to increase resource availability, facilitate long-distance trade within cost constraints, and achieve global bioenergy production targets.

5.2 Logistics, Quality, and Market Challenges that Inhibit Global Bioenergy Industry Expansion

The projected future demand for bioenergy presents economic development opportunity for regions that are rich in biomass resources: such regions represent potential "net suppliers" of renewable bioenergy. However, capitalizing on these opportunities by transporting biomass from areas of high production to areas of high energy consumption is inhibited because of logistics challenges influencing delivered feedstock cost.

Currently, feedstock cost is the major determinant of the viability of commercial-scale bioenergy production (Kenney et al. 2013). While many factors contribute to delivered feedstock cost (e.g., grower payment/stumpage fees, transportation, preprocessing biomass in preparation for conversion), long-distance biomass trade incurs additional costs largely due to inherent biomass characteristics and complex logistics (Hamelinck et al. 2005).

5.2.1 The Problem with Biomass

Raw biomass often lacks the qualities that enable it to be traded outside of its local production area, such as uniformity in format and chemical content, high bulk density, flowability within high-volume handling infrastructures, and storability. Lignocellulosic biomass exists in a variety of forms, including herbaceous biomass (such as agricultural residues and energy crops) and woody biomass (such as whole trees and residues). Because biomass is dispersed, it is often processed to facilitate handling prior to transport from the field. This introduces further variability in the biomass by creating a variety of formats, including round bales, square bales, chips, etc. This variability in chemical composition and physical characteristics (such as bale type, particle size and range, etc., generally termed "format") creates challenges to bioenergy producers that often have conversion processes that are highly sensitive to format and composition. In addition, the aerobically unstable biomass can rot during storage, resulting in dry matter losses and further degradation of quality.

Transportation and handling of low-density, cohesive, and degradable biomass materials are substantial barriers to a long-distance biomass feedstock supply system. If biomass could flow through conventional feeding, conveying, and storage systems, logistical costs could be greatly reduced. Unfortunately, many of the existing handling systems are optimized for small granular materials, such as food grains and minerals. These materials are non-cohesive, have small particle sizes and distributions, high densities, and are resistant to compression. In contrast, lignocellulosic feedstocks are often cohesive and have large particle size variations and low densities. They often are highly compressible, causing them to arch over hopper openings and plug mechanical and pneumatic conveying systems (Westover et al. 2011).

These challenges can be addressed by either (1) designing transportation, handling, and storage systems that accommodate the variety of types and formats of raw biomass or (2) formatting the biomass to be compatible with existing infrastructure. Leveraging existing transportation and handling infrastructure to move densified biomass is more feasible near-term and could potentially reduce supply chain costs. High-capacity, efficient, and effective technologies already exist that are capable of moving massive quantities of bulk solids and bulk liquids, such as rail and barge systems used in the grain, coal, and petroleum industries. These transportation modes have some restrictions, such as access to rail lines or waterways, as well as vessel capacity and minimum shipping distances; however, formatting biomass to be compatible with these infrastructures may offer significant cost savings over large distances.

For comparative analysis, it is useful to consider the development of other high-volume global industries— in particular how they responded to geographic imbalances of supply and demand and long-distance logistics challenges. Bioenergy feedstock supply system development is occurring in a very different environment than that of the fossil-fuel resources they are intended to replace or the agricultural commodities they are produced alongside. These industries evolved and became increasingly efficient in parallel with the evolution of transportation and communication networks. The liquid and solid systems developed to manage these commodities are the mature infrastructure that bioenergy trade can leverage for near-term efficiency and cost-effectiveness. For solid bioenergy feedstock trade, the grain trading infrastructure is a promising supply system model (Hess et al. 2009) and insightful case study.

5.2.2 Case Study: Global Grain Trade System

The physical characteristics of conventional energy feedstocks and many agricultural commodity products both enabled and helped shape today's transportation and handling infrastructures (Velkar 2010). Key points in the evolution of the global grain system provide useful illustrations of the influence of physical characteristics on inhibiting and enabling trade. For example, the shift that occurred in the first half of the 1800s in Chicago, Illinois, from transport of labor-intensive, sacked grain lots to agglomerated bulk-flowable lots, enabled the increased flow of grain so dramatically that the Chicago Board of Trade was uniquely positioned to respond to the expanded foreign demand for grain in the 1850s (Cronon 1991). The infrastructure developed during that time to transport and handle "the golden stream" of grain became the model that allowed grain to flow throughout the world.

In parallel to development of the grain industry infrastructure, advancements in communication both facilitated and necessitated standardization, certification, and regulation of grain product characteristics throughout the supply chain to assure that buyers received the appropriate quality of product for their needs and paid a fair price (Cronon 1991). As communication infrastructure developed following the advent of the telegraph, and information about quality and price could be shared more broadly and rapidly, opportunities for profit were more easily identified. The previously isolated economies of producers in different regions became more unified, as did prices offered for grain (Cronon 1991).

In the latter half of the century, the grain industry would undergo another major shift. The same advances that had helped integrate world grain markets also made local markets susceptible to uncertainties of competition, specifically volatility in market demand and price. In response to these uncertainties, the grain milling industry focused on preserving quality, identifying the best markets for different types of grain, and adding value to the grain product. Fractionation, or staged milling, of grain had a notable impact on increasing trade, as experienced in Minneapolis, Minnesota, when flour production rose from 200K barrels in 1870 to seven million barrels 20 years later and 20.4 million barrels by 1915 (Lass 1998; Storck and Teague 1952).

Industry leaders adopted technological and business innovations to overcome the natural disadvantages of the grain's physical and chemical characteristics, such as inconsistent protein content or incomplete blending of gluten and starch, which resulted in rapid rancidification (Storck and Teague 1952; Velkar 2010). Then, milling processes were re-engineered through adoption of technologies that improved both flour quality and shelf life, such as the middlings purifier, which removed husks from the flour, and the gradual-reduction process, which used a series of rollers to gradually pulverize the flour and integrate the gluten and starch. These technologies were scalable and in Minneapolis allowed milling capacity to grow from 490 metric ton/day (4,000 barrels) in 1880 to 1,470 metric ton/day (12,000 barrels) in 1905 (Danbom 2003). The large mills' size and improvements in product quality gave them (1) significant advantages to control cost of production and (2) influence on domestic and foreign markets.

5.2.3 Emulating Grain and Flour Industry Approach to Overcome Natural Disadvantages of Biomass

The same innovations that were implemented to overcome grain's natural disadvantages also increased supply chain costs, but the advantages of economies of scale and the value added to the product allowed grain and grain products to achieve market equilibrium. Fossil-fuel-based feedstock supply chains have addressed similar challenges and enjoy the benefits of a century (or more in the case of coal) of a well-established logistic infrastructure, which allows for low-cost and efficient transport of these energy carriers.

This is not yet the case for international biomass trade. Traders from Latvia, Portugal, Spain, and Sweden remark that the logistical requirements for feedstock collection often severely limit biomass supply, which, in turn, drives up prices. Transportation of preprocessed feedstock product is also problematic, especially if the conversion facilities are not close to waterways or railroads, and truck transportation over large distances is required. The cost of transportation over waterways also creates challenges, depending on the cargo size and port handling efficiencies (Wilmsmeier et al. 2006).

There are technological solutions that can overcome the natural disadvantages of biomass and fulfil logistical requirements. Consider torrefaction, for example. Torrefaction is a mild thermochemical treatment that takes place under atmospheric conditions and at temperatures ranging from 230–300 °C (Deutmeyer et al. 2012). This treatment has the potential to address several logistics challenges, such as improving bulk density and energy density and thereby reducing downstream transportation costs. Torrefaction also provides other benefits, such as lowering biomass moisture content while increasing material stability and increasing grindability (Tumuluru et al. 2011a). Torrefaction may also lower supply-chain cost by increasing energy density, particularly over large distances. It has been shown to be technically feasible for commercial and residential combustion and gasification applications (Tumuluru et al. 2011a). Upgrading feedstocks by improving energy density and oxygen-to-carbon ratio of the feedstock may make the product more valuable to bioenergy producers and increase demand (Deutmeyer et al. 2012). Particularly, using torrefaction to make biomass as similar to coal as possible would facilitate biomass co-firing in coal plants.

There are challenges for this approach that require further research. For example, torrefied biomass can be difficult to densify, requiring the assistance of a binder to receive high durability. Pelleting torrefied biomass also consumes more electricity than does pelletization of nontorrefied wood. Torrefaction is also limited in its ability to address feedstock property concerns for specific conversion methods, such as the high ash content in straw and some wood wastes, which can cause fouling or corrosion in thermochemical conversion reactors. Combining torrefaction and densification with other pretreatment technologies might mitigate these issues; however, the additional costs of preprocessing torrefied, pelleted biomass to address logistics challenges do not allow the feedstock to be cost-competitive with fossil-fuel-based counterparts (Fig. 5.2).

5.2.4 Implications for Bioenergy Feedstock Trade

The implications for bioenergy feedstock trade cannot be overlooked. Today's energy markets are based on tradable, low-cost, energy-dense feedstocks. Highly efficient and complex transportation and communication systems already exist.

The technologies for effectively addressing the tradability challenges of bioenergy resources also exist, but the advantages of scale and value-added products often fall short of achieving market equilibrium for many types of biomass resources (Fig. 5.2). For this discussion, a comparison of the properties that influence a product's tradability is adapted from van Vactor's (2004) dissertation on energy markets and commodity characteristics (Table 5.1).

The effectiveness of efforts to address feedstock logistics challenges, while also meeting consumer's quality requirements within cost thresholds, is a significant indicator of a feedstock's tradability and likelihood of market success. For example, the least preprocessed feedstock product shown in Table 5.1, forest residues, is not tradable outside its production area because of multiple logistics, quality, and market deficits. The most preprocessed feedstock product, torrefied wood pellets, overcomes critical logistics and quality deficits but is not economically feasible; thus, it has severe market characteristic deficits that restrict its tradability.

A fundamental requirement of expanding the bioenergy industry and enabling biomass trade is to balance the costs of transportation and preprocessing with feedstock value so that delivered feedstock costs allow access to more of the globally available biomass resource. A historical review of the global grain trading system demonstrates that this increases product accessibility; for example, following a reduction in cost, the grain industry experienced a rapid expansion (Velkar 2010). The proportion of British population consuming wheat increased throughout the nineteenth-century compared to consumption of other cereals; in 1800, about two-thirds of the population of Great Britain were estimated to have been consuming wheat, whereas by 1900, wheat consumption had become nearly universal, and consumption of oats and barley declined (Velkar 2010). This expansion was a result of many factors, but greatly enabled by reduction in price (Velkar 2010). A reduction in biomass delivered cost, enabled by cost-effectively addressing logistics challenges while meeting conversion facility specifications, could potentially enable the biofuels industry in a similar fashion.

5.2.5 Maritime-Specific Transport and Logistics Challenges

In general, mobility and durability are the principal logistical challenges that negatively impact feedstock delivered costs and restrict industry expansion. As previously discussed, central to these challenges is the poor flowability characteristics of most raw biomass (Westover et al. 2011). Bales, for example, must be individually (or in very limited numbers) loaded onto a truck from the field and driven to the bioenergy producers. The low bulk density of biomass prevents the truck from meeting its weight limit, further contributing to operational inefficiencies (Hess et al. 2009).

These challenges are magnified when maritime shipping becomes part of the supply system activities, as densities of common maritime cargoes vary from 0.6 tons/m^3 for light grains to 3 tons/m^3 for iron ore (Bradley et al. 2009). Additionally, maritime shipping presents unique transport and logistics challenges. Excessive

Table 5.1 Comparison of logistics, quality, and market characteristics of woody feedstocks–having undergone increasing levels of preprocessing to improve their tradability–in relationship to coal and crude oil competitors

		Forest residue	Wood chips	Wood pellets	Torrefied pellets	Coal/ crude oil
Logistics						
Divisibility	Equally and cheaply divisible; transferrable in small and large lots	✓	✓	✓	✓	✓
Non-hazardous	Low risk of danger if mishandled (affordable risk mitigation may be in place)[a]	✓	✓	✓	✓	✓
Mobility	Easily, efficiently, and affordably transported in existing infrastructure[b]			✓	✓	✓
Durability	Resistant to depreciation or degradation during storage and handling				✓	✓
Quality						
Substitutability	Can be consumed by multiple buyers, produced by multiple producers, or substituted for/by multiple products		✓	✓	✓	✓
Homogeneity	Consistent chemical and physical properties		✓	✓	✓	✓
End-use compatibility	Meets user-defined quality specifications at industrial scale			✓	✓	✓
Market						
Adequate demand	High product acceptance/ demand (market or policy driven)[c]			✓		✓
Reliable supply	High-volume production capacity		✓	✓		✓
Information transparency	Broadly communicated pricing, contracting structures, quality standards, and industrial regulation		✓	✓		✓
Market equilibrium	Cost-competitive with fossil-based market share					✓

[a] Each product has some risk associated with transportation and logistics (i.e., self-ignition; toxic off-gassing, dust explosion)

[b] Mobility can involve product attributes and infrastructure

[c] Note that the wood pellet industry is gaining momentum because there is market demand among bioenergy producers, mostly in Europe, who are willing to pay a high price for the feedstock due to subsidies or tax incentives (for example, carbon credits)

shipping costs are considered a major barrier, often surpassing the cost of customs duties (UNCTAD 2011). The cost of shipping biomass depends on many factors, including demand for shipping in general, reliability of biomass resources, shipping capacity, port efficiency, and feedstock characteristics (see Bradley et al. 2009; UNCTAD 2011 for further details).

One logistical challenge that is introduced with maritime transport is compatibility of biomass format with infrastructure at ports, which are the gateways for the international distribution of cargo. Ports have cargo loading/unloading equipment, storage for goods, as well as connection points for various transportation modes. The infrastructure and logistical management at ports are crucial to the efficient material loading and unloading, and therefore shipping costs (Bradley et al. 2009). Generally, the loading and unloading of dry and liquid bulk cargoes are suited for high-tech mechanized and computerized handling, and the specific practice depends on the average volume of trade of a certain type of cargo in the respective port (Bradley et al. 2009).

There are safety challenges associated with maritime transport of biomass. Wood pellets, for example, are safe when in bags; however, when shipped in bulk in large volumes, pellets are classified as hazardous material due to off-gassing of high levels of CO, CO_2 and CH_4, as well as spontaneous combustion potential (Bradley et al. 2009). Char can auto ignite into a smouldering fire when exposed to air or oxygen (Bradley et al. 2009). Mitigation strategies exist; however, the risks must first be well understood in order to implement the appropriate strategy.

5.3 Overcoming Logistics, Quality, and Market Challenges

As demand for bioenergy increases its share of world trade, supply systems that facilitate efficient transport of biomass from the field to the point of conversion must be developed. There are a variety of approaches to accomplish this, such as leveraging or adapting existing infrastructure; implementing technologies to make feedstocks more infrastructure-compatible; and implementing a combination of preprocessing, densification, and formulation technologies to improve feedstock physical, chemical, and economic performance within the supply system and conversion processes.

5.3.1 Leveraging or Adapting Existing Infrastructure

Where transport over rail or water is not possible, more efficient use of trucks, improvement of roads, and optimization of intermediate storage facilities or terminals may be viable options to overcome these logistic barriers. This is already occurring in some areas; for example, in Finland and Sweden several projects are underway to build up large biomass terminals. In the U.S. state of Georgia, an export terminal once used for the paper industry has been retrofitted to accommodate 1.35 million metric ton/year wood pellet export capacity (Geiver 2012). Similarly, the Port of Tyne in England is building new facilities for handling, storage, and transportation of wood pellets (Simet 2013).

5.3.2 Implementing Technologies to Make Feedstocks More Infrastructure-Compatible

One approach for implementing technologies to make feedstocks more infrastructure-compatible and lower feedstock cost is to locate preprocessing technologies as near as practical to the production location (Hess et al. 2009; Searcy and Hess 2010). This facilitates change of the feedstock's physical format to improve density, flowability, stability, consistency, and quality. Making the biomass format compatible with existing high-capacity transportation and handling infrastructure, such as that used in the grain, coal, and petroleum industries, will reduce the need for new infrastructure. Producing biomass with these characteristics at a cost conducive to energy production requires the development of new technologies, or improvements to existing ones. There are some key characteristics of biomass that are targeted to reduce supply chain costs, including moisture management, density, and quality.

There are many examples of technologies under development that have the potential to revolutionize the bioenergy industry by reducing biomass cost. For example, new drying technologies are being developed to manage moisture content (e.g., greater than 25 %), a common biomass characteristic (Shinners et al. 2007). Although drying technologies exist, many have significant capital and/or operating cost.

Efforts to increase energy and volumetric density, by preprocessing raw material into formats that are easily transported and handled, will have a significant impact on total costs. Eventually, increased preprocessing capital and operating cost will dilute this savings. However, the net effects as witnessed in the market are still very positive, and represent the single highest cost-reduction possibility along the whole value chain supplying biomass feedstock to bioenergy producers.

Densification via pelletization has been demonstrated to successfully address some logistical challenges and may offer benefits to biochemical conversion platforms as well (Theerarattananoon et al. 2012; Rijal et al. 2012; Shi et al. 2013; Ray et al. 2013). Densification of comminuted wood particles into pellets results in an increase in energy per cubic meter by a factor of four to five in respect to wood chips, which was necessary to enable international trade of low-value wood for energy purposes. However, this is still well below the energy density of competing energy carriers such as coal, and therefore further increases of density are needed.

As suggested by the earlier discussion of torrefaction, there are technologies under development that, in combination, could potentially revolutionize the bioenergy industry. These technologies address barriers associated with economic biomass supply, including a short operational window, low bulk density, high moisture (and therefore instability), and other quality challenges.

By itself, torrefaction is a potentially low-cost method of increasing energy density by reducing the biomass of approximately 20 % of its volatiles and achieving near-zero moisture content (Tumuluru et al. 2011a). While torrefied wood offers a number of benefits over raw wood, torrefied biomass has low bulk density and is not economical to transport over long distances. Further, the brittleness of torrefied biomass can lead to large proportions of explosive dust, requiring the torrefied product to be classified as a hazardous good and resulting in negative cost impacts. Combining torrefaction and densification (i.e., torrefied compacted biomass [TCB] pellets) can increase the energy density of biomass approximately fivefold (Deutmeyer et al. 2012). Combined torrefaction and densification also produces a biomass feedstock better suited for blending with coal, offering improved milling and handling characteristics, and allowing the two to be blended prior to coal milling, which can potentially increase co-firing ratios (Tumuluru et al. 2011a). By addressing feedstock diversity challenges (Deutmeyer et al. 2012; Tumuluru et al. 2011a) and improving supply chain logistics costs for long-distance maritime transport (Fig. 5.3), TCB pellets have the potential to increase available biomass resources by improving supply/demand economics and expanding the quantity of biomass that is available for energy production.

The absolute cost effects in Fig. 5.3a are calculated on basis of freight when employing a Handy size (15,000–35,000 ton) or Handymax size (35,000–58 ton) dry bulk carriers. These absolute figures do not apply to all situations, as shipping markets are volatile and change of vessel size can have significant cost effects as well. Figure 5.3b illustrates such potential savings by increasing both energy and volumetric density of wood by torrefaction and pelletization in comparison to just pelletization on selected routes using appropriate vessel sizes (i.e., Handymax and Panamax [60,000–80,000 ton]). The cost effect comparing white wood pellets at 625 kg/m^3 and 17GJ/mt with TCB pellets at 700 kg/m^3 and 21 GJ/mt is approximately minus 0,76\$/GJ, or nearly 13\$/mt. The cost savings illustrated are not limited to shipping and can be achieved along the entire logistical chain.

Logistics costs, despite often being charged per weight, are mostly determined by available transportation volume for higher-stowing cargo, while handling is charged purely on a weight basis. Hence, cost advantages of approximately 37 % can be achieved in rail, barge, and oceangoing-ship transport where volume and not weight is the limiting factor in comparison with wood pellets on a per GJ basis, while for loading and unloading, as well as for trucking, a 23 % advantage is realistic since both are calculated or limited by weight (Deutmeyer et al. 2012).

5.3.3 Implementing Technologies to Manage Feedstock Variability

One feedstock trade challenge is the variability of biomass, which includes a variety of materials that have a range of chemical characteristics and material formats. This variability is a not only a challenge for conversion processes, but material handling systems as well.

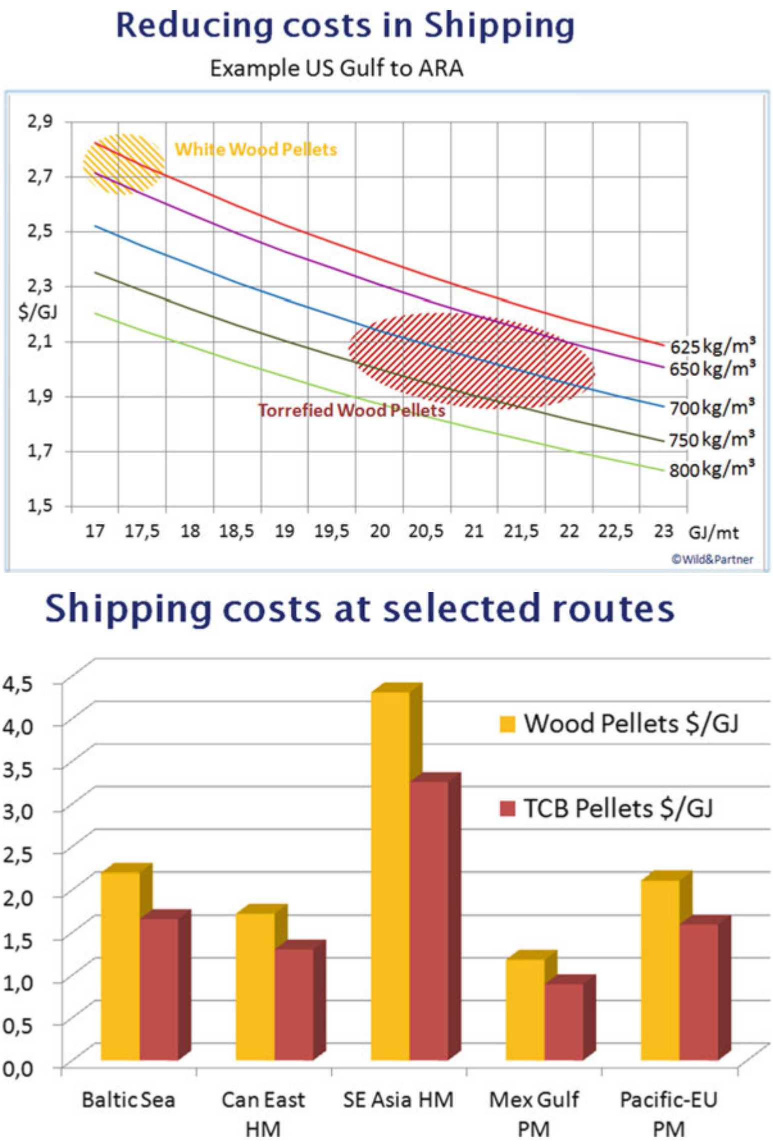

Fig. 5.3 Illustration of reduced shipping cost potential enabled by the use of torrefied compacted biomass (TCB) pellets to increase both energy density and bulk density: (**a**) the cost effect of increased energy density at constant volumetric density of the pellet and (**b**) differences in shipping costs of wood versus TCB pellets (Wild 2012)

In most conventional, locally produced bioenergy production arrangements, the heterogeneity of biomass is the burden of the conversion facility. This can require conversion facilities to have a variety of capital-intensive transportation and handling equipment, which may be economical when relying on a local feedstock resource, but effectiveness over a range of scenarios is limited. Different handling systems, such as conveyors and pneumatic conveyance pipes, have different feed handling requirements. The problem is aggravated by the large variability within each feedstock as well as between the different feedstocks.

Developing equipment systems that will handle the full range of variability of a given region could be extremely challenging, and likely cost prohibitive. By controlling the variability of feedstock parameters, such as particle size (including distribution) and moisture content within and between the feedstocks, the constraints on the handling systems can be greatly relaxed (Kenney et al. 2013). In addition to establishing a limited number of consistent formats, addressing quality characteristics within each format is also an issue. Biomass is highly variable in terms of carbohydrate and ash content, for example, which are two parameters than can have a significant impact on a conversion process. Conversion processes are optimized for certain material specifications, and therefore consistency of in-feed material is also important.

Fractionation of biomass can generally be divided into two types of processes: chemical and mechanical. Chemical fractionation is typically an integral part of the pretreatment process, while mechanical fractionation takes advantage of the variability in biomass characteristics, either whole or ground, to separate the biomass into different streams of varying utility and value. The latter provides an opportunity to improve biomass quality and reduce costs associated with the transport and use of biomass through fractionation. Examples of chemical fractionation include steam explosion, ammonia fiber explosion, and dilute acid hydrolysis. The intent of chemical fractionation is to disrupt structure of the lignocellulosic matrix and/or isolate the cellulose of the biomass to improve the efficiency of enzymatic reactions.

There are many benefits that can be achieved via fractionation. Using mechanical fractionation technology, low-value whole biomass can be upgraded by separating it into multiple streams and co-products with different uses and values. Improvements in size uniformity can enhance flowability, and enable the delivery of on-spec feedstocks to the refineries. Fractions high in ash can be removed to make the feedstock more suitable for thermochemical conversions. The removal of unwanted fractions prior to transport will reduce costs. Mechanical fractionation can also increase the value of the feedstock by concentrating the more desirable elements in the collected fractions. There are several mechanical methods that can be used to fractionate biomass, including fractionation based on particle size, material density, and anatomical or botanical fractionation.

Fractionation technologies have enabled numerous commodity markets, including the international grain industry. The grain milling technology in use around 1870 was relatively unchanged for over a 100 years since steam milling had reduced the industry’s dependence on wind and water (Velkar 2010). The use of millstones continued for grinding wheat with limited improvements in the intervening period. This grinding method ensured that the wheat grains were ground thoroughly and as quickly as possible; however, the flour obtained contained a significant proportion of unwanted bran. New developments in milling technology involved improvement and perfection of roller milling techniques, which produced whiter flour with only slightly less yield. The main advantage of this new technology was improved quality, and the whiteness of flour obtained for the same proportion of grains used to produce the coarse 'household' grade flour using the older grinding technology (Velkar 2010). The speed and broad adoption of roller milling was shaped by at least three factors: increasing domestic demand for white flour, unsuitability of softer domestic wheat varieties to the technology, and increase in the imports of foreign flour and hard wheat varieties (Velkar 2010).

There are parallels with the bioenergy industry, which is seeing an increasing demand for biomass to meet long-term biofuels and national renewable energy production goals and, subsequently, the need for quality feedstocks.

5.4 Least-Cost Formulation to Enable Industry Expansion

A feedstock concept designed to increase available biomass resource within cost constraints is least-cost formulation of feedstocks to improve logistics, quality, and market characteristics simultaneously. A formulated feedstock combines various feedstock qualities, types, or constituents to get a blended material that is affordable and meets the in-feed requirements. This approach may combine high-quality, high-cost material that meets or exceeds the in-feed requirements and blend it with low-quality, low-cost material. This process has three objectives:

1. Reduce the overall cost of the material by blending high-cost and low-cost resources
2. Reduce variability of the final blended feedstock by blending to a certain criteria
3. Bring more material into the supply system by enabling use of resources that otherwise would not be suitable for conversion (Muth et al. 2013).

Least-cost formulation enables feedstocks to play an important role in economically and efficiently converting biomass into bioenergy products. It may involve intermediate preconversion steps that break down, clean up, stabilize, and make biomass more reactive to biochemical and thermochemical conversion. This concept combines various preprocessed biomass resources and/or additives to produce an on-spec feedstock that has good physical transferability, durability, and is tradable as a commodity (Muth et al. 2013).

Formulation can also be used to mitigate the effects of undesirable components in raw biomass resources, such as ash. The resulting feedstock will provide consistency and lower costs to bioenergy industries because they can design their processes around a single feedstock that is crafted from numerous, variable resources.

Least-cost feedstock formulation has the potential to overcome logistics and quality challenges for achieving environmental and economic targets, which will require a significant increase in the amount of biomass that is used for bioenergy production. A modeled case study of the effect of least-cost formulation in increasing biomass resource available for bioenergy production is shown in Fig. 5.4 (Muth et al. 2013).

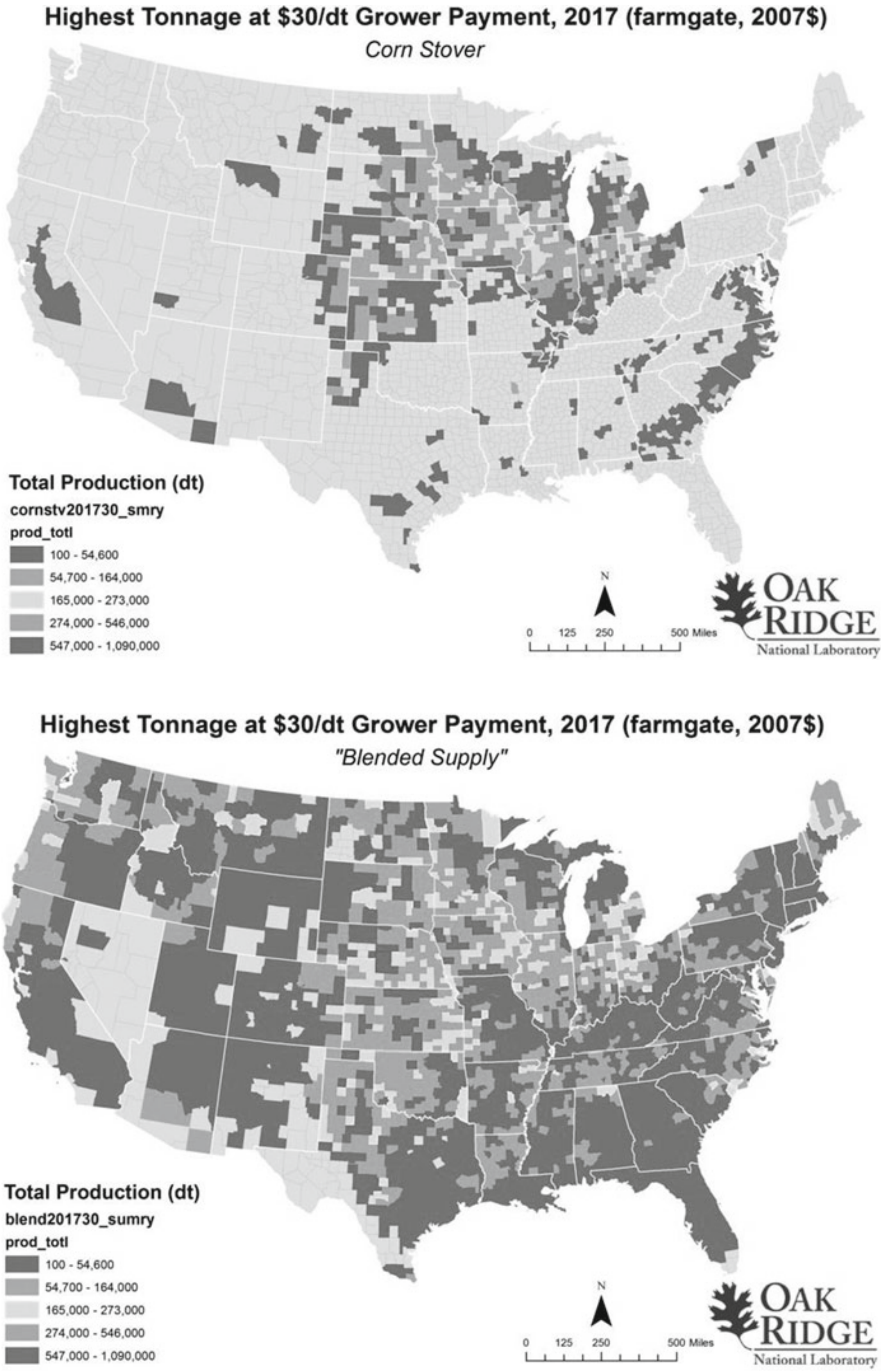

Fig. 5.4 Least-cost formulation increases the biomass resources entering the system by combining high-cost biomass with lower-cost biomass, resulting in a blendstock that meets cost targets. The top map shows feedstock availability in a stover-only scenario (**a**), and the lower map shows the increased availability in a blended supply scenario (**b**), The modeled feedstock blend includes corn stover, perennial grasses, and other biomass resources including thinnings and logging residues (Muth et al. 2013) (Data extracted from the Knowledge Discovery Framework, https://bioenergykdf.net/)

5.5 Conclusions

A barrier to the expansion of this industry is that biomass is not always geographically where it needs to be, nor does it have the tradability characteristics required for efficient handling, storage, and conversion, due to low energy density compared to fossil fuels. Technologies exist that can address these challenges; however, the associated costs often result in a delivered feedstock cost that is not cost-competitive with fossil fuels.

Two key barriers that impact the market success of biomass are mobility and durability. Many biomass forms, such as bales and woodchips, are low in dry matter bulk density. Torrefaction, a thermochemical treatment that drives off moisture and volatiles, produces an energy-dense, stable, and easily transported feedstock product. The product lacks bulk density, which can be improved using densification technologies such as pelletization to increase dry matter bulk density and address feedstock mobility and durability issues that are coupled to long-distance transport and logistics. There are many advantages to densification, including improved handling and conveyance efficiencies, controlled particle size distribution for improved uniformity, improved stability, quality improvements, and improved performance in conversion systems (Tumuluru et al. 2011b). Currently, however, these technologies are often energy intensive and too costly.

As demand for bioenergy increases, the amount of feedstock resources required to support production will be significant. To meet feedstock needs, a typical biorefinery may receive a variety of feedstocks ranging from switchgrass to corn stover to miscanthus to eucalyptus, depending on location and availability. These feedstocks vary widely in composition and recalcitrance, and would require biorefineries to optimize (and possibly re-engineer) their processes for each different type of biomass, thus increasing costs. Complicating this further is that feedstock diversity varies markedly from region to region, and each feedstock within a region varies from year to year based on weather conditions, handling, storage, and crop variety. This will result in different types of biorefineries needed in every region which will further increase costs for construction and operation since there will be no "standard" biorefinery.

Least-cost formulation, in conjunction with mechanical preprocessing and preconversion technologies, offers a promising solution to these issues by combining feedstocks to achieve desired feedstock specifications, reduce undesirable properties, and simplify downstream processing. This approach leverages technology advances to address transport and logistics challenges and convert raw biomass into feedstocks that are easily traded outside their production areas.

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